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Reconciling predator conservation with public safety

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Research Communications

Reconciling predator conservation with public safety

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Global loss of predators calls for increased conservation of these crucial ecosystem components However, large predators can also threaten public safety and adversely affect economic activities, creating conflicts between different public interests. In the ocean, although many shark species are facing worldwide declines, recorded instances of unprovoked attacks by sharks on humans have been increasing, stirring public concern and generating radical policies such as culling. Here we show that despite increasing records of white shark (*Carcharodon carcharias*) attacks in California, the individual attack risk for ocean users has decreased by >91% over a 63-year period (1950 to 2013). The decrease in risk could be explained by an undetected long-term shark population decline and/or changes in behavior and spatial distribution of people and sharks, the latter possibly associated with the recovery of pinniped (Phocidae and Otariidae) populations. Promoting safer behaviors among human ocean users could prove orders of magnitude more effective than culling, while meeting the dual goal of improving public safety and conserving endangered marine predators.

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Reconciling the expansion of human activities with conservation of endangered predators is an increasingly important issue in both marine and terrestrial ecosystems (Ripple *et al*. 2014). Documented declines of large predators have caused major losses of ecosystem health and services – benefits that nature provides to people (Estes *et al*. 2011; McCauley *et al*. 2015). Reductions of lions (*Panthera leo*) and leopards (*Panthera pardus pardus*) in sectors of sub-Saharan Africa have led to population increases of olive baboons (*Papio anubis*), which in turn has led to higher rates of intestinal parasite infections among their populations and humans living in close proximity (Brashares *et al*. 2010). Overfishing of large predatory sharks in the coastal Northwest Atlantic was linked to the collapse of a century-old fishery for bay scallops (*Argopecten irradians*) in North Carolina as a result of an overabundance of cownose rays (*Rhinoptera bonasus*), which prey on scallops but were controlled numerically by the once-abundant predatory sharks (Myers *et al*. 2007). Yet efforts to protect and recover large predators may also result in high personal risk for people and domestic animals sharing the same environments. Recent analyses have highlighted recoveries of carnivores in human-dominated European landscapes (Chapron *et al*. 2014), but the question of how widespread this coexistence model can be remains open. Here we address this issue for the marine environment.

In coastal areas around the world, the number of unprovoked shark attacks on humans has grown at a steady pace (Burgess 2015). In western Australia, in the past 3 years there have been seven deaths from shark bites (Gross 2014). Recently, 12 attacks resulting in five fatalities occurred off Reunion Island in the Indian Ocean (Séret 2014). These events elicit intense media and public attention, and prompt local governments to take radical actions, including shark-culling campaigns, to improve beach safety (Curtis *et al*. 2012; Neff and Yang 2013).

Culling is predicated on the assumption that increasing shark attacks are driven by greater shark abundances. Nevertheless, alternative explanations exist. More people in the water, easier communication of shark encounters facilitated by the internet and social networks, and changes in shark and human distributions and behavior can increase the number of shark attacks on record (Curtis *et al*. 2012). Under these scenarios, culling may be ineffective in reducing public risk and instead may remove sharks from populations that are already depleted.

In light of the poor conservation status of many shark species globally (Dulvy *et al*. 2014), culling already threatened populations might be irreparably detrimental for their persistence, cause unforeseen ecosystem effects (Ferretti *et al*. 2010), and have negligible effects on public safety (Curtis *et al*. 2012). In Hawaii, for example, no change in attack rate was detected following the intentional eradication of 4668 sharks around the Island of Oahu in response to a surge in shark attacks during the 1960s (Wetherbee *et al*. 1994).

Analyses of long-term shark attack records and human ocean use statistics can provide quantitative assessments of changes in shark bite risk in a region, identify the possible factors contributing to encounters between sharks and people, and inform alternative measures to avert or minimize the occurrence of injurious interactions (Neff and Yang 2013). Here, we analyzed these data from coastal California, a well-monitored ocean sector where most attacks are attributed to white sharks (*Carcharodon carcharias*). After decades of unregulated exposure to offshore and coastal fisheries, the Northeast Pacific (NEP) white shark population is predicted to experience a phase of growth due to (1) a reduction in fishing mortality; (2) improved protection at the state, federal, and international level; and (3) impacts of climate change; and increased availability of food resources (Dewar *et al*. 2013). Using records of shark bites and statistics on human ocean use, we addressed the hypothesis that risk has increased over the past decades and evaluated whether a coexistence model between large predatory sharks and people is feasible under expanding human ocean use.

Methods

Probability framework

The probability of a shark attack can be modeled as the joint probability of multiple processes: the probability that a person and a shark encounter one another $p(E)$, that such an encounter results in a bite $p(B)$, and that the attack is communicated $p(C)$. $p(E)$ depends on the abundance of humans (H) and sharks (S) in the water, and on the spatial overlap between people and sharks (O). If we assume that – for any given encounter – $p(B)$ and $p(C)$ remain constant, then the probability of a shark attack depends only on H, S, and O. Because shark attacks are rare and discrete events (Curtis *et al*. 2012), it is reasonable to assume that the number of attacks per unit time and location (observation unit) follow a Poisson distribution that can be a function of covariates reflecting H, S, and O. By using this probability framework, we analyzed data on shark attacks recorded in California and information on local human ocean use (commercial or recreational activities exposing people to shark encounters [eg surfing, diving, and beach visitation]) to estimate the expected number of attacks at any time and the location per unit of people predicted to be in the water, and to predict changes in attack risk over time and space.

Shark attack data

Data on shark attacks were extracted from the Global Shark Attack File (WebPanel 1; GSAF 2014). We selected only shark attacks recorded in California between 1950 and 2013 that involved the white shark and resulted in injuries. Injurious white shark bites often result in the victim's hospitalization, and consequently, we expected that few cases, if any, would have failed to be recorded and communicated even in historical times (thus ensuring that $p[C]$ was constant throughout the study period).

Ocean use data

For the same period, we constructed time series of population abundance for California coastal counties adjusted for seasonal and weekly patterns of coastal beach going (WebPanel 1). We also constructed time series of annual indices of people engaged in the main ocean activities of the attack victims: surfing, scuba diving, abalone (*Haliotis* spp) diving, and recreational swimming (see Results section). Surfing was quantified in terms of surfing events per year, scuba diving as annual diving days by certified scuba divers, and abalone diving as annual diving days recorded in abalone fisheries; swimming intensity was predicted by estimating the annual number of coastal beach visits (WebPanel 1).

Estimating standardized attack rates

Temporal and spatial covariates associated with each attack record, and data on ocean use, were used to estimate: (1) the expected number of attacks at any given time and location per unit of human ocean use (attack rate); (2) the corresponding individual risk of experiencing a shark attack; and (3) the change in (1) and (2) over time and space.

Because data on ocean use were available at different spatial and temporal resolutions, we estimated attack rates at two different levels of spatial and temporal aggregation. Initially, we estimated a standardized attack rate for each county, year, month, and victim activity. We fitted a generalized linear model (GLM) with a Poisson distribution and a log link function (the logarithm of the distribution mean is a linear function of the model predictors) to the number of attacks recorded in each observation unit, and used the county-specific adjusted monthly index of coastal population abundance as an offset term (equivalent of dividing the number of attacks by the number of people present in coastal areas while retaining the probabilistic model framework; WebPanel 1). This aggregation level allowed us to detect seasonal, annual, and spatial patterns of attack rates and test whether there were differences in attack rate across victim categories. We assumed that human ocean use was proportional to human density in proximity of the coasts and to the seasonal and weekly propensity of people to visit the shore for recreation (WebPanel 1). In fact, within coastal California, recreational ocean use (surfing, diving, and oceangoing) has increased at a faster rate than the growth of the state's human coastal population. To account for this pattern, we then used the more detailed indices of ocean use (available only at the state level). Accordingly, for each victim category, we aggregated the attack data at the state level, fitted a Poisson GLM to the annual number of attacks recorded in California, and used the victim-specific index of activity intensity as an offset term (WebPanel 1).

Finally, to estimate an overall change in risk of shark attack, we stacked all activity-specific time series together and estimated an average instantaneous rate of change of standardized attack rate by fitting a Poisson generalized linear mixed-effects model (GLMM) to the annual number of attacks by victim category, using the activity-specific index of ocean use as an offset term, and treating victim activity as a random effect (WebPanel 1).

Results

Between 1950 and 2013 there were 86 injurious attacks –13 of which were fatal – attributed to white sharks along the California coast (Figure 1a). Throughout this period, there was an average of 1.37 attacks per year with an increasing trend, from an average of 0.9 attacks per year in the 1950s to about 1.5 attacks per year in the final 10 years (from 2004 to 2013; Figure 1b). Attacks clustered close to areas of high human population density, such as southern California between San Diego and Orange counties and in proximity to San Francisco Bay, as well as in sparsely populated areas to the north between Del Norte and Mendocino counties (Figure 1a). Incidents were recorded progressively closer to northern elephant seal (*Mirounga angustirostris*) colonies (Figure 2a), reflecting the sharks' coastal aggregation in proximity to their primary prey (Brown *et al*. 2010; Dewar *et al*. 2013).

During the same period, human ocean use for commercial and recreational purposes increased with increasing human population and easier access to the coastal ocean (WebPanel 2). Human population in coastal California tripled, from 7 million inhabitants in the 1950s to 21 million in 2013 (Figure 1c). Ocean activities increased at much faster rates. There were about 7000 surfers in 1950, and more than 872 000 in 2013 (a 125-fold increase). Likewise, the estimated number of certified scuba divers was about 2000 at the beginning of the 1960s and about 408 000 in 2013 (a 204-fold increase), while beachgoers increased from approximately 53 million in the 1950s to about 165 million in 2013 (Figure 3a; WebPanel 2).

After weighting shark attack numbers by the coastal human population, we detected a decline in attack rate by 2.4% annually, amounting to a 78% reduction between 1950 and 2013 (WebTable 1). Attack rate varied throughout the year, being highest between October and November, and lowest between March and May (Figure 1d); this pattern matches the seasonal occurrence of sharks in California waters detected with satellite and radio-transmitting tags (Jorgensen *et al*. 2010), and from records of shark attacks on seals, sea otters (*Enhydra lutris*), and cetaceans (Klimley and Ainley 1996). However, seasonality changed over time (Figure 1d). In the 1960s, attacks had a less obvious seasonal trend, peaking at the end of November. In subsequent years, this seasonal variation became increasingly more pronounced, and the peak moved progressively toward the beginning of October. Finally, attack rate increased from southern to northern California and was above detectable levels only in areas where large adult sharks are known to congregate (Dewar *et al*. 2013). Peak attack rates were detected around San Luis Obispo and Mendocino counties (Figure 1e).

Surfers were attacked most frequently (33%), followed by abalone divers, scuba divers, and swimmers (27%, 14%, and 14% respectively; Figure 2b). Modeling attack rates while controlling for the numbers of people engaged in each of these activities highlighted that abalone diving was the activity most prone to shark incidents, followed by surfing, scuba diving, and swimming. In 2013, the chances of a shark attack on an abalone diver were one in 1.44 million or close to 0.69 attacks for every million diving days. For scuba divers, they were 0.007 per million (or one attack for every 136 million diving days). For surfers, the chances were one in 17 million. Swimmers had the lowest chance of shark attack, with one attack for every 738 million beach visits (0.0014 attacks per million beach visits; Figure 3).

Individual, activity-specific attacks showed significant declines for scuba and abalone divers and for swimmers, but not for surfers (Figure 3c). Standardized attack rate for scuba divers declined by more than 99.67% (confidence interval [CI]: 99.98–93.56) between 1962 and 2013. For abalone divers, attack rates declined by about 97.46% (CI: 99.58–84.68) between 1959 and 2013. For swimmers, attack rates declined by about 81.49% (CI: 95.69–20.48) between 1950 and 2013. Overall, when all individual estimates of temporal change in attack rate were combined, there was a significant decline in attack rate of about 91.24% (CI: 96.42–78.55) over the entire period (1950–2013) (Figure 3; WebTable 3).

Discussion

Analysis of shark attack trends off California supports a coexistence model of ocean users and large sharks. Similar to analyses conducted on land (Chapron *et al*. 2014), policies aimed at protecting large marine predators and predicted to promote recovery of the NEP white shark population (Dewar *et al*. 2013) are not associated with increasing risk to people. On the contrary, California ocean goers are safer today than at any other time since the 1950s due to a significant decline in the risk of injurious shark encounters. Such a pattern might be evident in other regions with records of increasing attacks, once the intensification of human ocean use is taken into account (Curtis *et al*. 2012; Burgess 2015).

If attack rate is taken as a proxy of white shark abundance, these results raise the question of whether white sharks have in fact declined in California, and warrant further investigations on the status and current trajectory of the NEP population. In particular, data are needed on the total amount of fishing-related mortality that white sharks are exposed to in international waters and Mexican waters, as current estimates are incomplete and highly uncertain (Dewar *et al*. 2013).

The decline in attack rate off California could also result from a change in the sharks' spatial distribution in response to parallel recovery of other large marine animals. White sharks respond to changing prey population abundance (Klimley and Ainley 1996; Brown *et al*. 2010; Skomal *et al*. 2012). Recovering pinniped populations in California (WebPanel 2) might have influenced movement and spatial distribution of white sharks in coastal areas, concentrating these predators near pinniped rookeries and away from areas frequented by ocean users. Elephant seals, in particular, influence the predatory behavior of local white sharks (Pyle *et al*. 1996; Brown *et al*. 2010). After being completely eradicated from California in the 19th century by overhunting, elephant seal colonies were gradually re-established in the past six decades due to a northward range expansion from Isla Guadalupe, Mexico (WebPanel 2). Sharks returning from their offshore phase (WebPanel 1) might now spend less time roaming in inshore areas in search of food and instead go directly toward pinniped colonies, thereby reducing the probability of encountering people. The detected decline in distance between shark attacks and elephant seal colonies (Figure 2a), and the change in attack seasonality with peaks moving toward the haul-out season of juvenile elephant seals (Le Boeuf and Laws 1994), are consistent with the hypothesis that white sharks have been tracking their major prey's population dynamics (WebPanel 2).

Finally, behavioral changes of sharks and humans might also explain a decline in interactions. Sharks may avoid highly populated areas or, because of the increased availability of preferred prey such as pinnipeds, may be less inclined to explore alternative food resources. This potential mechanism is particularly important because it would indicate that effective conservation of endangered marine populations may also result in greater public safety. People may have also learned where and when sharks occur and thus adapted their behavior when engaging in ocean activities. For example, some aspects of surfing (preference for timing activities at dawn or dusk, and selecting particular locations where conditions are ideal) are difficult to change and might partly explain why the decline in attack rate on this victim category was not significant (see WebPanel 2 for other caveats associated with surfers). These hypotheses remain untested.

Although the reasons for the declining attack rates need to be evaluated with additional data, we demonstrated that the probability of shark bites is extremely low. According to statistics of the Centers for Disease Control and Prevention (www.cdc.gov), in California, a person is 1817 times more likely to die by unintentional drowning than from a shark attack and is 6897 times more likely to be hospitalized for decompression sickness when diving (Dardeau *et al*. 2012) than being a victim of a shark bite. Nonetheless, shark attacks do occur, and thus the concern and need for policy makers and natural resource managers to address the risk is justified. We suggest that an in-depth analysis of available attack data can inform alternative strategies that are more efficient than culling, and that will improve beach safety while protecting threatened shark populations. For instance, our results show that in California it is 1566 times safer to surf in March between San Diego and Los Angeles as compared with surfing between October and November in Mendocino. In Mendocino County, risk decreases by about 24 times if surfing in March. These are order-of-magnitude decreases in shark bite risk that have never been demonstrated with culling (Curtis *et al*. 2012), and can be used to promote safer behaviors for ocean users (ie avoiding riskier locations and seasons). Attack statistics for shark species (white sharks and others) and auxiliary data on ocean use from other regions could be analyzed in depth, as we have done here for California. These analyses may reveal spatial and temporal patterns of attack rate, determine whether bite risk has actually increased or decreased, investigate possible causes, and inform management strategies to address public safety and risk perception by the public (eg through ocean user associations such as scuba diving or surfers' organizations, and natural resource management agencies, such as those responsible for managing wilderness parks). This approach could be applied to other carnivores, both in marine and terrestrial environments, to inform policies and behaviors aimed at supporting the coexistence of people and potentially dangerous predators.

Large predators, including sharks, are important ecosystem components and public safety is a priority, but meeting the seemingly conflicting goals of protecting people and large predators is possible. Any initiative aimed at reducing populations of sharks and other top predators should be based on careful consideration of their abundance, conservation status, the potential ecosystem effects of these actions, and, importantly, the costs, benefits, and rationale of alternative actions. An improved understanding of the behavior, distribution, and ecological role of sharks, as well as the factors influencing the risk of shark bites, may ultimately be the most effective way for humans to stay safe while enjoying nature.

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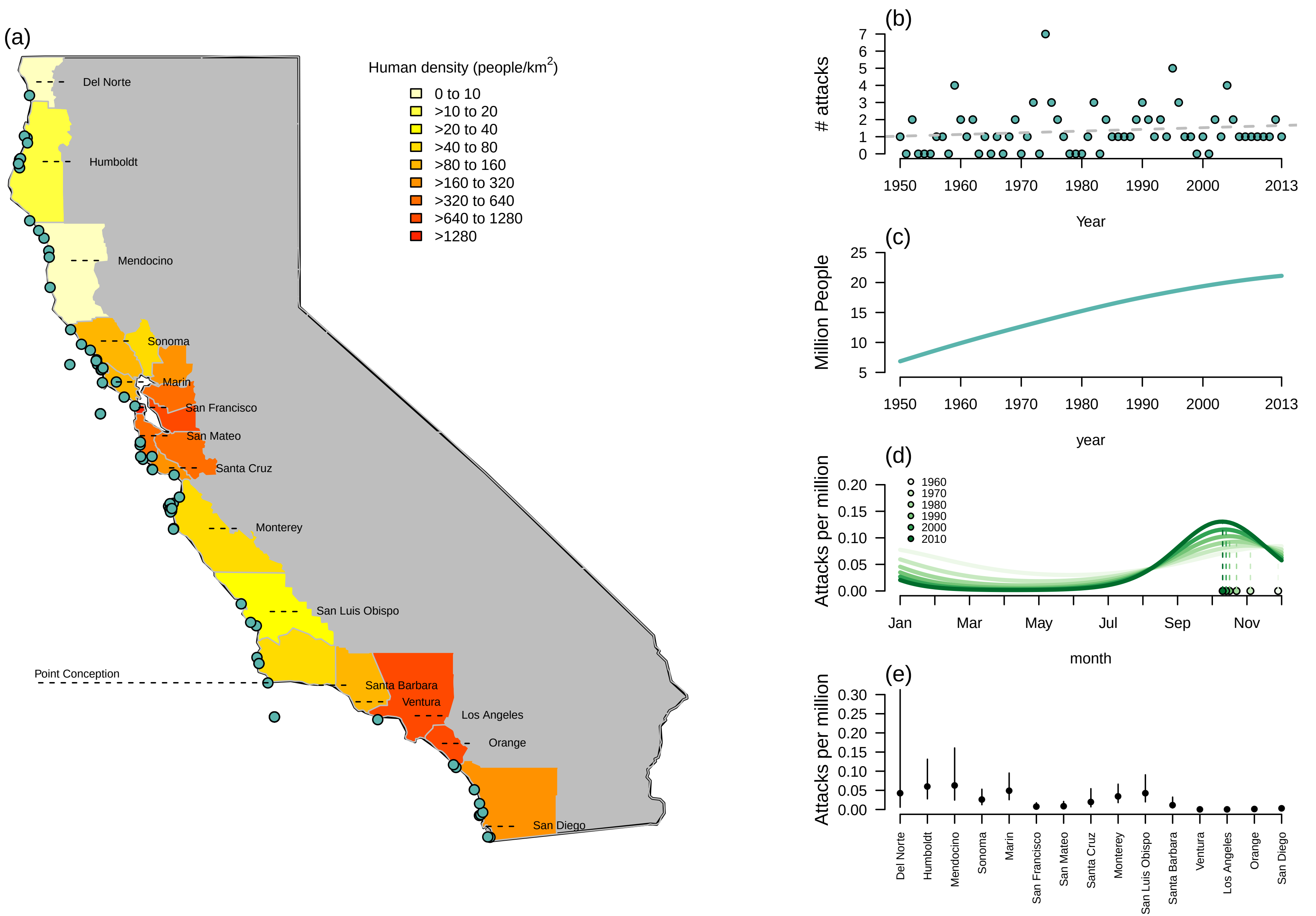
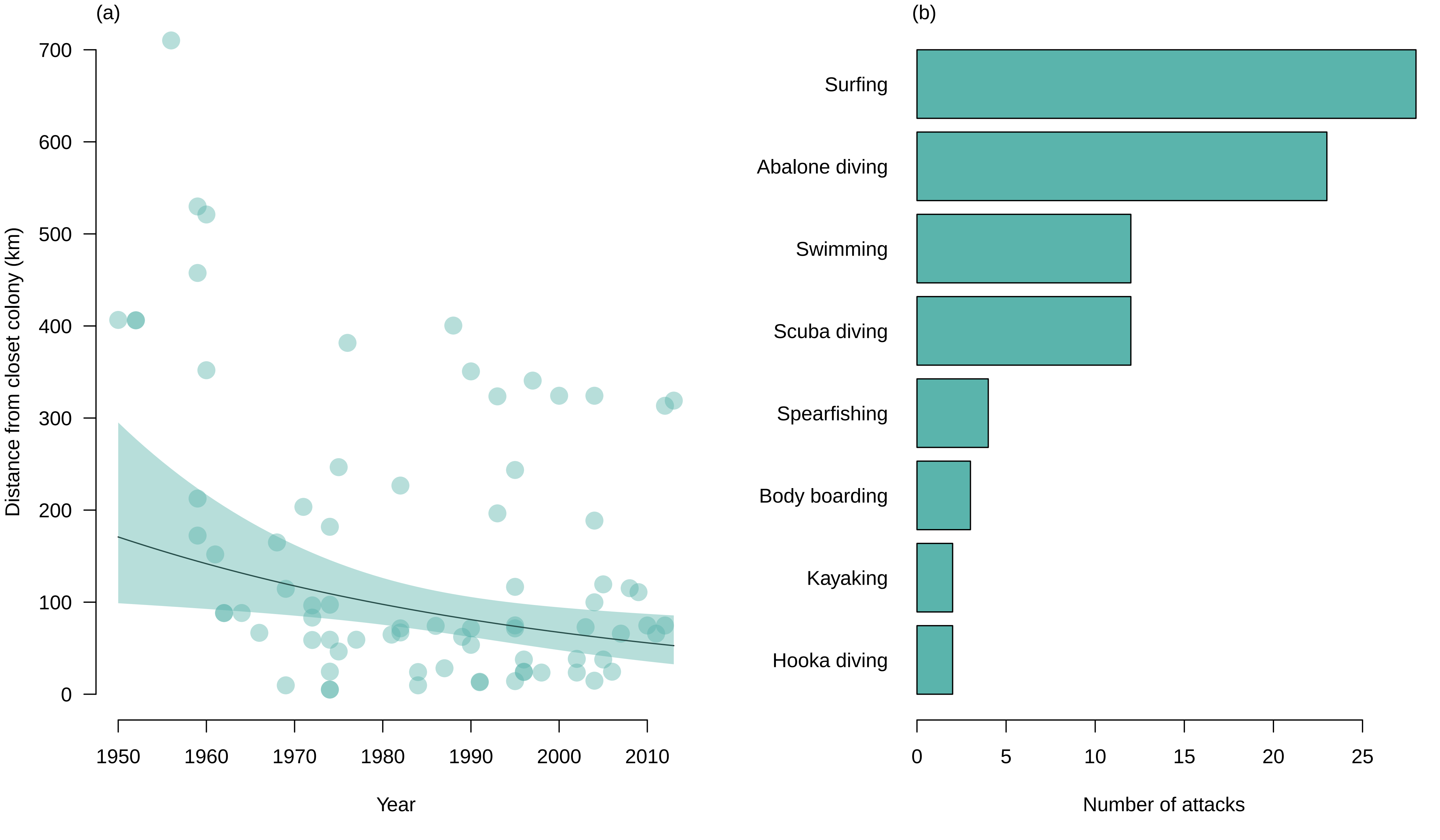
Figure 1. Geographic and temporal patterns of shark attacks. (a) Map of shark attacks and human population density in California coastal counties; attack positions have been slightly offset to facilitate identification of single attacks in nearby locations. (b) Time series of annual number of attacks (a

regression line has been superimposed on the points). (c) Growth curve of California coastal population. (d) Seasonal variation of standardized attack rate; dots indicate peaks of the attack rate across decades; note a shift from early winter to mid-fall. (e) Changes in attack rates across counties; counties have been ordered from north (left) to south (right). Error bars indicate 95% confidence intervals.

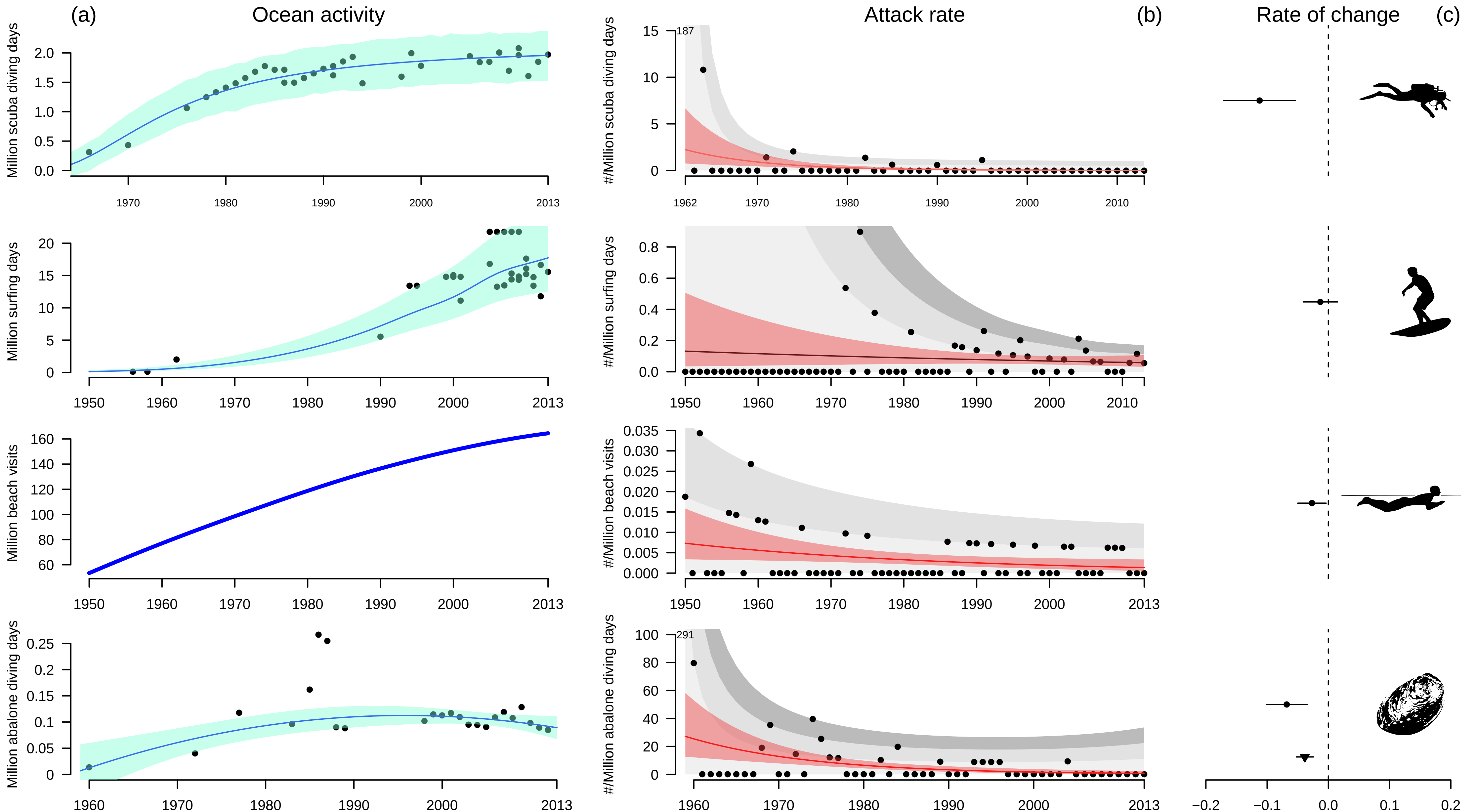
Figure 2. (a) Temporal changes in the distance of attack from the closest elephant seal colony. The trend line represents a significant exponential model between distance from the closest colony and year ($log(Distance) = 41.5 - 0.019 * \text{Year}$; $R^2 = 0.078$). The blue polygon represents the 95% confidence intervals around this model. (b) Number of attacks sorted by victim activity.

Figure 3. Change in attack rate by victim activity. (a) Trajectories of people's engagement in ocean activities (ie offset variables) used to standardize the activity-specific attack rates (b). Red polygons in (b) represent 95% confidence intervals (CIs) around the trend line. Gray polygons highlight the discrete nature of the attack data (ie there were only one, two, or three attacks per year per victim category). (c) Instantaneous rates of change (IRS) of attacks. Dots and superimposed segments are the independently estimated activity-specific IRS and 95% CI; the triangle is the IRS of the attacks combined together.


(a)
Human density (people/km^2)
0 to 10
>10 to 20
>20 to 40
>40 to 80
>80 to 160
>160 to 320
>320 to 640
>640 to 1280
>1280
Del Norte
Humboldt
Mendocino
Sonoma
Marin
San Francisco
San Mateo
Santa Cruz
Monterey
San Luis Obispo
Point Conception
Santa Barbara
Ventura
Los Angeles
Orange
San Diego
(b)
attacks
Year
1950 1960 1970 1980 1990 2000 2013
(c)
Million People
year
(d)
Attacks per million
1960 1970 1980 1990 2000 2010
Jan Mar May Jul Sep Nov
month
(e)
Attacks per million
Del Norte Humboldt Mendocino Sonoma Marin San Francisco San Mateo Santa Cruz Monterey San Luis Obispo Santa Barbara Ventura Los Angeles Orange San Diego



(a)
(b)
Distance from closet colony (km)
700
600
500
400
300
200
100
0
1950
1960
1970
1980
1990
2000
2010
Year
Surfing
Abalone diving
Swimming
Scuba diving
Spearfishing
Body boarding
Kayaking
Hooka diving
0
5
10
15
20
25
Number of attacks



(a)
Ocean activity
Attack rate
(b)
Rate of change
(c)
Million scuba diving days
#/Million scuba diving days
187
Million surfing days
#/Million surfing days
Million beach visits
#/Million beach visits
Million abalone diving days
#/Million abalone diving days
291